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Geotechnical aspects of earthen construction materials

Aspects géotechniques des matériaux de construction en terre

C.E. Augarde[*1], J.C. Smith[1], A. Corbin[1], D. Ciancio[2], C.T.S. Beckett[2] and P.A. Jaquin[3]

[1] *School of Engineering and Computing Sciences, Durham University, Durham, UK*
[2] *School of Civil, Environmental and Mining Engineering, University of Western Australia, Australia*
[3] *Land Development and Exploration, Warkworth, New Zealand*
** Corresponding Author*

ABSTRACT Earthen construction and soil-based construction materials (SBCMs) are expanding areas of interest worldwide. They offer the potential for low carbon and embodied energy, sustainability through recycling and an alternative to high energy materials such as fired masonry. The materials that are generally used in earthen construction can be identified as manufactured unsaturated soils. Until recently, however, these materials have rarely been studied using a geotechnical approach, and there is a general lack of recognition of the key mechanisms at work mechanically and hydraulically. In this paper we review geotechnical aspects of soil-based construction materials examining the effects of suction and environmental conditions, and demonstrating behaviour in shear, compression and fracture. We cover materials which are both unstabilised, where the primary source of strength is suction, and materials which are stabilised with cement, lime or fibres. The review is backed up by experimental results from laboratory and field testing undertaken over a number of years at Durham and UWA.

RÉSUMÉ Construction en terre (en utilisant "des matériaux de construction à base de sol - ») est une extension du domaine de l'intérêt dans le monde entier en raison de faibles émissions de carbone potentiel et l'énergie intrinsèque , et la durabilité à travers le recyclage , et il est possible d' utiliser beaucoup plus pour remplacer les matériaux de haute énergie tels que la maçonnerie tiré . Les matériaux qui sont généralement utilisés dans la construction en terre peuvent être identifiés comme les sols non saturés fabriqués . Jusqu'à récemment, toutefois , ces matériaux ont rarement été étudié en utilisant une approche géotechnique , et il ya un manque général de reconnaissance des principaux mécanismes à l'œuvre mécaniquement et hydrauliquement . Dans cet article, nous examinons les aspects géotechniques des matériaux de construction à base de sol - examinant les effets de la succion et des conditions environnementales , et le comportement en cisaillement démontrer , la compression et de fracture. Nous traitons des matériaux qui sont à la fois stabilisées , où la première source de force d'aspiration est , et les matériaux qui sont stabilisés avec du ciment , de la chaux ou de fibres . La revue est soutenue par expérimentales ré- sultats de tests en laboratoire et sur le terrain entrepris depuis un certain nombre d'années à Durham et l'UWA .

1 INTRODUCTION

Earthen construction is a term describing the use of subsoil for the construction of walls, and other structural members, used by Man for thousands of years and still in widespread use around the world. Although stereotypically associated with developing countries, its use is far more universal; for instance, there are many examples of recent structures with earthen components in Western Australia and California. Geotechnical engineers also carry out earthen construction but tend not to call it that, e.g. the excavation, filling and compaction operations to construct an earth dam could be classified as a form of earthen construction, but it is not.

The differences between the geotechnical use of soil to create structures and the commonly accepted meaning of 'earthen construction' are that, in the latter, soils tend to be less saturated and formed into thinner sections, behaving more like structural elements such as slabs and beams. However, there is no reason why geotechnical concepts cannot be applied to earthen construction, and this may be the key to bringing these materials into wider use, through improved scientific understanding of their mechanical and hydraulic behaviours. In this paper we make the link between earthen construction, generally a subject for structural engineers to date, and geotechnics, demonstrating the fertile area of research opportunity this presents to geotechnical engineers and illustrating this with some of the research work we have carried out.

2 EARTHEN CONSTRUCTION

Earthen construction (EC from here) can be classified into unit-based and *insitu* forms. In the former class are materials such as adobe (soil plus straw bricks, dried in the sun) and compressed earth blocks. The distinction between these EC materials and masonry is the lack of firing of units (thus making the EC materials lower energy). In the latter class are materials like rammed earth (RE) and cob which are compacted into place at their final location, with or without formwork.

Examples of all types of EC construction materials can be found around the world, many examples of which are very old: indeed the way that the materials and their use spread over time is an interesting subject in itself (Jaquin et al. 2008). Parts of the Great Wall of China and the Alhambra in Granada are made of EC materials (Jaquin & Augarde 2012). As an example, Figure 1 shows rammed earth in a medieval structure in Andalucia. As stated above, EC is of long standing but still in use throughout the world; as another example, Figure 2 shows a rammed earth building in Western Australia.

Figure 1: Medieval RE structure in Southern Spain

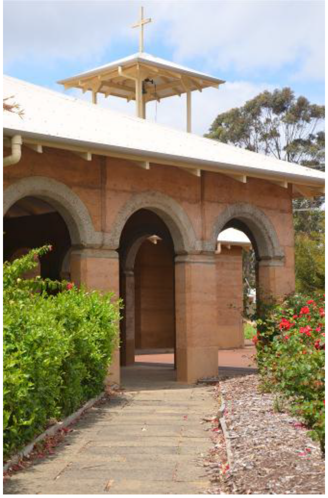

Figure 2: Modern RE structure in Australia

3 GEOTECHNICAL ASPECTS

Unstabilised EC materials are created from mixtures of natural subsoils. A typical rammed earth mix might comprise 20% silty clay, 70% sand and 10% gravel fractions by mass. Rammed earth mixes are wetted to optimum water content and compacted into place in layers. Stabilised EC materials contain a binder in addition to the soil materials, usually cement or lime. Heritage structures sometimes contain a range of other stabilisers or reinforcement such as bone or even animal hair.

The technical literature on EC materials is surprisingly sparse and most attempts at characterisation, to assess strength for instance, take a “structural engineering” view of the material as homogeneous and isotropic with a strength linked to some hidden cohesion. There are many studies describing tests on samples of EC showing how changes in certain fractions alter the compressive strength but very little explaining why the changes might be present.

Unsaturated soil mechanics is a vibrant area of geotechnical research, as most readers here will be aware, and there is general acceptance that partial saturation of soils leads to increased strength through suction and other adsorbtive effects (Gens 2008). There is considerable research activity in this area, to develop constitutive models using a variety of alternative stress measures, to quantify water retention relationships and development of laboratory equipment especially devices to measure suction in the laboratory or the field (e.g. Toll et al. 2011). It is only very recently, however, that the connection has been made between suction in unsaturated soils and the strength of unstabilised EC materials. The first publication that we are aware of that makes this link is the conference paper of Gelard et al. (2007), and in the geotechnical literature Jaquin et al. (2009) present the first laboratory tests including the measurement of suctions in EC materials. The latter tests were constant water content, unconfined compression tests on unstabilised rammed earth samples where the suctions were measured during testing using tensiometers. A clear link was shown between suction and strength, an example of which is shown in Figure 3 where shear strength (as deviator stress) is plotted against suction as the tests proceed. The suctions measured here are much lower than those found in the field after drying, however the principle is clear.

It appears then that there is merit in considering earthen construction materials as *manufactured unsaturated soils*, and to develop constitutive models of mechanical and hydraulic behaviour from a geotechnical point of view. There is evidence that this approach is gaining interest, via recent papers (e.g. Nowamooz & Chazallon 2011) and a keynote at the most recent International Conference on Unsaturated Soils (Gallipoli et al. 2014). In fact, this is the approach taken by the authors for the past 5 years and below we describe selected research in this area.

4 GEOTECHNICAL INVESTIGATIONS OF UNSTABILISED MATERIALS

4.1 Tensile strength

The tensile strength of EC materials is a key factor in areas such as seismic resistance and crack repair in

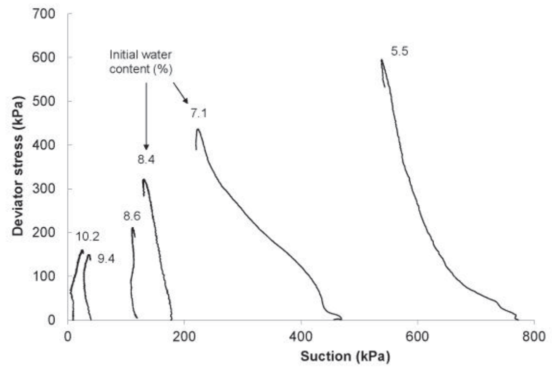

Figure 3: Results from unconfined compression tests on unstabilised RE including suction measurements. (from Jaquin et al. 2009)

heritage structures. However, it is often hard to obtain, especially for unstabilised materials. The Brazilian test is widely used in rock mechanics and comprises the compressive loading of a disc of rock across a diameter. The disc fails in tension via a crack linking the load application points and, assuming elastic behaviour, one can obtain the average tensile stress (and hence tensile strength) along the fracture. Beckett (2011) includes work showing the applicability of this simple test to earthen construction materials, concluding that samples of 50 or 100mm diameter yield the most convincing results. In later work (Beckett et al. 2014) use is made of this test in a study of the effect of salinity in the pore water on the tensile strength of RE. Figure 4 shows one set of results for a mix with silty clay, sand and gravel in proportions 2-7-1, respectively. For this mix the effect of salinity in the pore water is at odds with previously published work and an explanation (contained in detail in the paper) is based on the low clay content of this particular mix. This study has interest outside of earthen construction materials, in agricultural soils in areas at risk of saline water intrusion. Results from Brazilian testing applied to RE (in a slightly different format) appear also in a recent paper by Bui et al. (2014).

4.2 Microstructure

Key to the more widespread adoption of EC materials is the ability to design properties, just as is done with compressive strength and concrete. The key source of strength in unstabilised materials is

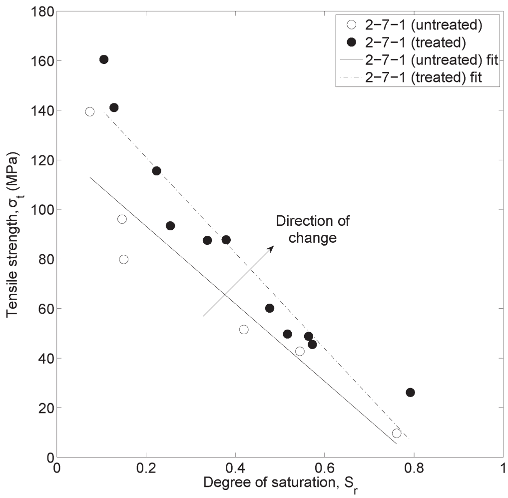

Figure 4: Tensile strength of RE with and without saline pore water (from Beckett et al. 2014).

acknowledged to come from suction, which itself is affected by the microstructure of the soil matrix. Microstructure, i.e. the void size distribution (VSD), is a function of the particle size distribution of the soil mix and the compaction procedure and not the latter alone as a number of studies have proposed.

Methods for determining the VSD of a soil sample have a long history, with mercury intrusion porosimetry (MIP) being an established technique. However MIP works with very small samples of soil and is not suitable for earthen construction materials where there is a wide range of particle size.

For this reason, attention has switched to the use of non-destructive techniques which can deliver information on the internal structure of porous media, for example x-ray computed tomography (XRCT). A Zeiss Versa 410 XRCT machine has been operating in Engineering and Computing Sciences at Durham University since 2013, with EC materials being one of the key materials scanned. Initial work using a machine at Nottingham University, UK, (Beckett et al. 2013), and a desktop machine (Smith et al. 2014) has been built on more recently as described in Smith & Augarde (2014), where the potential for the use of XRCT for scanning soil mixtures is examined. There is a conflict in XRCT scanning between wishing to obtain the highest resolution and the largest area of coverage. One can rarely achieve both, and with a compacted material with a range of particle sizes (like a RE mix for instance) one cannot see right "down to the clay". Instead a pragmatic approach must be adopted where sample size is chosen to balance the capabilities of the XRCT machine and the desire for representative samples (i.e. a very small sample will scan well but is unrepresentative of a mix where there could be large particles present). Three sections from scans undertaken for different sample sizes (cylindrical 12, 38 and 100 mm dia.) are shown in Figure 5 where one can see the detail revealed by the scanning. The conclusion of this study is that the optimum choice is the 38 mm dia. sample, balancing the XRCT issues stated above with the need for ease and reality of laboratory testing.

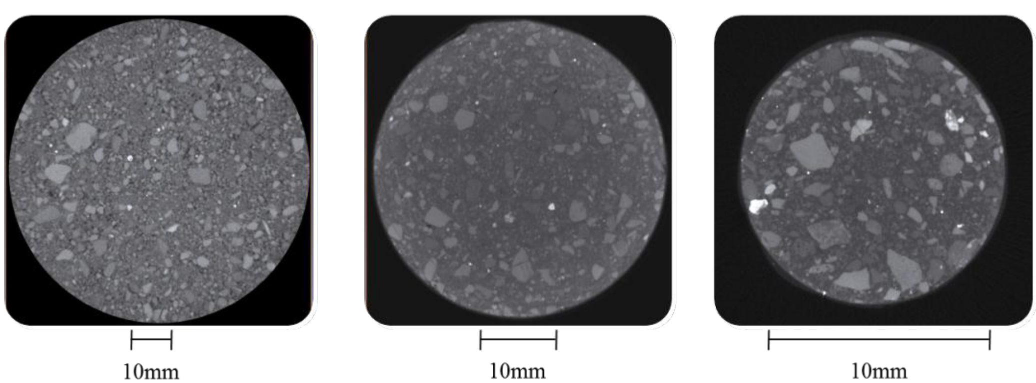

Figure 5: XRCT scans of cylindrical rammed earth samples of different diameters (100, 38 and 12 mm) showing microstructure at different scales (from Smith & Augarde 2014)

Figure 6 shows the type of information one can only obtain from scanning. Plots of VSDs in 38 mm diameter samples of a RE mix before and after unconfined compressive loading are shown (D = detailed scan; T = top of a compaction layer; B= bottom of a compaction layer; F = full sample scan). The volume of voids in the sample increases during loading, due mainly to cracking in the sample. Work is currently ongoing attempting to link the VSDs observed with the water retention curve and hence to suction as one of the sources of strength (Beckett & Augarde 2013).

5 GEOTECHNICAL INVESTIGATIONS OF STABILISED MATERIALS

Cement stabilised rammed earth (CSRE) is a more recent construction technique, where cement is added to the soil mix in quantities that vary between 5% and 15% by mass. First, cement is mixed with the dry soil, then water is added to the mix which is finally compacted inside formwork. This process must be quick enough to avoid the hydration of the cement during the compaction phase.

Although suction also exists in CSRE, its contribution to the strength of the material is not likely to be as significant as that generated by the hydrated cement bonds. The compressive strength of CSRE is generally higher than that of unstabilised RE and, depending on the properties of the soil mix, can reach values as high as 22 MPa (Ciancio et al. 2012).

Current research is investigating the optimum water/cement ratio to use in CSRE. Although the most popular practice by rammed earth practitioners remains that of using an amount of water corresponding to the optimum water content of the mix independently from the cement content used, there is no scientific evidence that this method generates the highest strength. The following doubts arise:
1) If the water content is equal to the optimum, would it be enough to hydrate all the cement in the mix? Should the answer be no, the CSRE mix would be inefficient and, more importantly, unsustainable;
2) Is it appropriate to compact the soil mix to reach its maximum dry density considering that the strength contribution of suction is far less significant than that of the cement bonds?
3) Would the concrete theory also apply to the case of CSRE, according to which the lower the water/cement ratio, the stronger the hydrated cement byproducts hence the higher the strength? If that were the case, then construction practices might have to change and for CSRE it would be preferable to obtain a compacted material with dry density lower than its maximum, and with an initial water content lower than its optimum able to produce better hydrated cement bonds. This issue has been preliminary identified and studied in a recent work (Beckett & Ciancio 2014) but further investigation is still needed.

On the face of it CSRE appears to be similar to cement-stabilised soils, some studies of which appear in the geotechnical literature, however it is important to note that the latter are at much higher saturation levels and lower compaction, so comparisons may not be fruitful.

6 FUTURE OPPORTUNITIES

The examples of research presented above only scratch the surface of what could be investigated. We have carried out other work not reported here on the effects of wetting and drying cycles, on the use of reinforcement (geogrids and fibres) and development of site-based tests. While the main focus in the EC industry is strength rather than stiffness, there is scope for standard triaxial testing of EC materials with the aim of developing constitutive models. This will be challenging as the very low water contents of these materials *insitu* leads to brittle behaviour, which is notoriously difficult to accommodate in plasticity models. We have carried out limited experimental work on fracture (Corbin & Augarde 2014) but have thus far presented the materials behaviour in the framework of the fracture mechanics of concrete, rather than soil mechanics.

A final comment to make is the recommendation that those of us involved in teaching the next generation of geotechnical engineers at universities make EC material behaviour the subject of final year projects. In our experience these projects are very popular with students and may lead to drawing more young people into geotechnics.

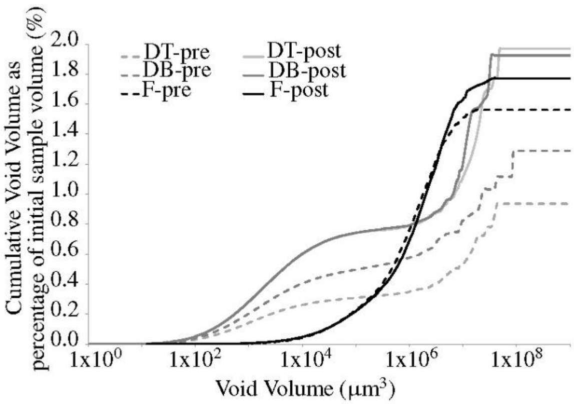

Figure 6: VSDs for samples scanned before and after compression loading.

7 CONCLUSIONS

There is considerable interest worldwide in improving our understanding of the behaviour of earthen construction materials both as they appear in heritage structures and also for new build. They present the potential for serious environmental gains as replacements for some uses of fired masonry and concrete. To achieve this we have to improve our scientific understanding of the materials and the way ahead is definitely geotechnical.

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